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REALIZATION OF ADAPTIVE CONTROL ALGORITHMS WITH THE AID OF ONBOARD DIGITAL COMPUTERS

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ABSTRACT. Discussion of practical factors which must be considered during synthesis of adaptive control algorithms ensuring optimal values of a specific control-system quality functional with allowance for the actual state of the physical environment and for the parameters of the plant's input and output coordinates. The study is limited to flight-vehicle control systems with onboard digital computers. The choice of a most suitable type of digital computer is shown to depend on the complexity of required algorithms, process rates, necessary degree of accuracy, weight and geometry restrictions, adaptability to other computational capabilities. Energy-source limitations in prolonged spacecraft flights demand the use of extensive control procedures that select control impulses required for spacecraft rotation about the equivalent Euler axis during orientational corrections. The synthesis of such a system is demonstrated.

The solution of today's control problems necessitates the use of onboard digital computers as components of control systems. Control problems can be solved today by using onboard digital computers. /7

The problem of using onboard digital computers as components of control systems has become particularly timely and important in connection with the technological realization of adaptive (self-adjusting) control systems. In connection with this, we are faced with the specific problems of studying the dynamics of automatic control systems including an onboard digital computer, of determining the basic characteristics of onboard computers, and their relationship to the dynamic characteristics of the vehicle.

The present report discusses certain problems arising in connection with the realization of adaptive control algorithms in automatic control systems.

An adaptive control algorithm will be defined as a changing program of operations, which takes into account the actual state of the surrounding medium, the parameters of the input and output coordinates of the object, ensures optimal values of a given control system quality functional, optimality being defined in a specific way.

Similarly, an adaptive control system will be defined as a system realizing an adaptive algorithm in the above sense.

Onboard digital computers show great promise as far as their application to control systems governing the motion of flight vehicles is concerned. The effectiveness of the use of an onboard digital computer in a control system is determined by the possibility of using principally new methods of solving control problems, methods that will improve the indicators of a control system as a whole.

The use of onboard computers is based on the following basic features:

a) great logical and computational capabilities, permitting one to solve diverse and complicated problems with a practically unlimited accuracy; /8

b) stability of operation within a wide range of operating conditions;

c) high speed, making it possible to simultaneously solve several control problems;

d) high level of adaptation and self-control of the control system.

The onboard computer presents the control system designers with great opportunities with respect to designing complicated adaptive control algorithms. The resulting control systems have a higher reliability both as a result of a programmed correction of errors in the functioning of certain reserved control system elements and due to the direct control of the apparatus during its functioning.

In designing control systems involving an onboard digital computer we are faced with the following technical problems:

1) One must analyze the structure of a control system in order to determine a version which has the highest reliability and lowest cost.

2) One has to determine rational demands on the onboard computer.

3) One must organize economic parallel programs for solving problems on the onboard computer.

4) The programs for the onboard digital computer must be executed in real time making sure that problems of various degrees of importance are solved with various degrees of reliability (i.e., various degrees of influence on the freedom from

accidents in the flight), and making sure that the time requirements of various subscribers to the onboard computer are satisfied.

5) One must use the multichannel structure of the control system and the digital computer in order to write programs such that the reliability of the most important control algorithms will be increased.

6) The onboard digital computer programs must be debugged on general-purpose digital computers with the aid of simulation programs.

7) The onboard digital computer programs must be debugged on an analog-digital complex.

The onboard computer used in the control systems of flight vehicles must perform a large number of operations involved in solving the following functional problems:

1) navigation and control of flight vehicles in various stages of the flight;

2) collection and processing of information about the surrounding medium;

3) solution of auxiliary problems, control of the operating conditions of individual units, selection of optimal flight regimes, etc.

An important feature of control systems and control involving the use of an onboard digital computer is the fact that the computer makes it possible to change the control program in a flexible adaptive and automatic manner, and to make decisions on the basis of an appraisal of the situation.

The onboard digital computers may be classified according to various basic features that permit us to place them in a certain class. /9

One of the possible classifications which defines the place and the purpose of an onboard digital computer in a control system is as follows:

a) command onboard digital computers which execute strict control according to a predetermined program, independently of the course of the process under control;

b) compensating onboard digital computers which are used in rigid control loops dependent on the load;

c) informational onboard digital computers; in this case the information about the state of a system is processed, received by humans, and in the final analysis used to control the system;

d) regulating onboard digital computers used in a closed control loop; this form of application is most important and shows great promise, the location and the tasks of the computer may be extremely diverse.

The use of onboard digital computers in control systems places particularly great demands on the following indicators of the quality of a computing system: weight, volume, reliability, power needed, operating temperature range, radiation resistance, transfer of vibrations, and others. In addition, a number of specific demands are placed on the onboard digital computer itself. The control system involving a digital computer must: 1) operate reliably without preventive maintenance and servicing during the effective service period or the flight of the vehicle. This means that the digital computer, consisting of thousands of components, must have an acceptable service life (in the case of an onboard unit which is impossible to repair, the service life is equal to the time interval to the first failure). 2) The range of problems solved by the onboard digital computer as a rule remains the same in the course of the entire service life of the machine. 3) The data input and output must be done in real time and within strictly defined time intervals. The onboard digital computer must be such that it can be used for a wide range of tasks since it may be necessary to make changes in the scale of the telemetry data, and computations necessary for the preparation of the initial data, etc.

When one synthesizes a control system with a digital computer one is free to specify the following parameters:

1) program execution time;

2) speed, characterized by the time needed to execute a short operation;

3) system of commands,

4) precision (number of digits);

5) storage capacity

The program execution time is determined by the maximum permissible length of the time interval for the most dynamic control algorithm executed on the onboard digital computer.

The program for the onboard digital computer has a complicated structure and consists of subprograms realizing the individual control tasks and of standard subprograms realizing typical control and data conversion algorithms; a subprogram adjusting the special and standard subprograms in accordance with the operating regimes, time, and control signals from the outside, and a subprogram of initial states, storing the initial codes in the cells of the operative memory, requiring a certain initial state of the operative memory. /10

The selection of the type of the onboard digital computer is determined by:

1) complexity of algorithms;
2) speed of processes;
3) required accuracy of algorithm execution;
4) allowable weight and size;
5) ease of conversion to other problems;
6) freedom fron interference;
7) capacity to organize control of the control system.

The demands placed on the onboard digital computer, as well as on its structure and the structure of the I/O units, depend on the concrete problems and algorithms.

Depending on the type and purpose of an aircraft, the onboard digital computer may solve the following problems:

1. Information processing. 2. Computation of controlled quantities. 3. Formation of control signals. 4. Control functions. Problems belonging in this group, particularly navigational algorithms, require higher computational accuracy. In this case the word length of the onboard computer should contain

no less than 20 - 24 bits, and the speed should be at least 50 - 80 thousand of operations per second.

The control of the onboard equipment by means of an onboard digital computer consists of algorithms of automatic control along with a mechanism for the prediction of malfunctions within the time in which the basic problems are being solved. In order to solve control problems one has to increase the fixed and operative storage capacity of the onboard computer.

Certain characteristics of foreign onboard digital computers, based on third generation elements, are shown in the table.

Usually, an onboard digital computer should ensure a realization of a large number of algorithms, and thus it is important to first consider those algorithms that constitute the greatest computational load (η):

$$\eta = \frac{A}{A+L} \qquad (1)$$

where A and L — are the number of simple arithmetic and logical operations.

Those algorithms include first of all algorithms involving information processing and computation of control quantities. /11

The structure of the onboard computer should be maximally adapted to the totality of the onboard systems, to the problems solved, and should be optimal according to a definte design criterion. It is clear that it is necessary to have a certain number of possible design versions.

Onboard digital computer	Purpose	Speed, E^{op}/sec	Storage, in words	Number of bits	Reliability in hours	Weight, kg	Volume, dm^3	Power, Watt
H 387	Navigation, guidance, & control (X-15)	50	Operative storage 4096 Storage-32768	24	10.000	16.8	28.3	90
	Flight control (F-111)	100-200	8.192-32.768	16	2.500	22.5	22	—
F opr CR*	Data processing	200-400	16.384-131.072	16.32 61	—	34	52	—

Unfortunately at the present time there is no established procedure for solving the above problem, although there exist approaches permitting a formalization of the problem.

The increasing restrictions on the energy losses involved in the orientation of flight vehicles on a trajectory with a long time of flight (on the order of 1 year) force us to look for new, more economical methods of controlling the motion of the craft about its center of mass. One of such methods involves an extensive control of the orientation, which is possible by using a control system with an onboard digital computer it it. The method consists in essence of a selection of moments, applied to the craft about the axes attached to it, such that the craft begins to move about the axis of equivalent rotation (the Euler axis).

As compared with the existing method which is used at the present time, the method of extensive control ensures the solution

*Translator's note: CR designates control relay.

As compared with the existing method which is used at the present time, the method of extensive control ensures the solution of the basic orientation problems with, other things being equal, much smaller energy losses (approximately two times smaller) and much faster (approximately 2 - 3 times). However, the realization of extensive control involves an execution of a relatively large volume of arithmetic operations which assumes the use of an onboard digital computer. It is characteristic that the use of an onboard digital computer in extensive control systems is the necessary condition of their technical realization. In addition, the use of an onboard digital computer is justified by considerable savings in the energy and time of execution, which makes it possible to increase the time of the active existence of a craft, and improve its tactical and technological characteristics without any additional losses. /12

Let us consider the principal problems involved in the construction of extensive control systems with an onboard computer, paying particular attention to the physical meaning of the problem and the onboard computer functions necessitated by the problem.

The control problem may be stated as follows. Suppose that we are given the initial ($t = 0$) and the final ($t = T$) angular position of a craft, determined by the modified Euler angles ψ, ν, and γ, with a given system of constraints.

We are required to determine a program giving the variation in time of the bounded control moments M_1, M_2, M_3, applied to the craft about the axes attached to it, such that the movement of the craft from its initial to final position will occur during:

1) a minimum time T_m,

2) a given time T with minimum energy losses.

It is assumed that the craft is an ideally rigid body, and the effect of external disturbances on the angular motion of the craft while under control is negligibly small.

Without giving the detailed calculations, we note that the problem of extensive control has an exact analytical solution. This circumstance is of great importance in establishing the functional objective of an onboard digital computer.

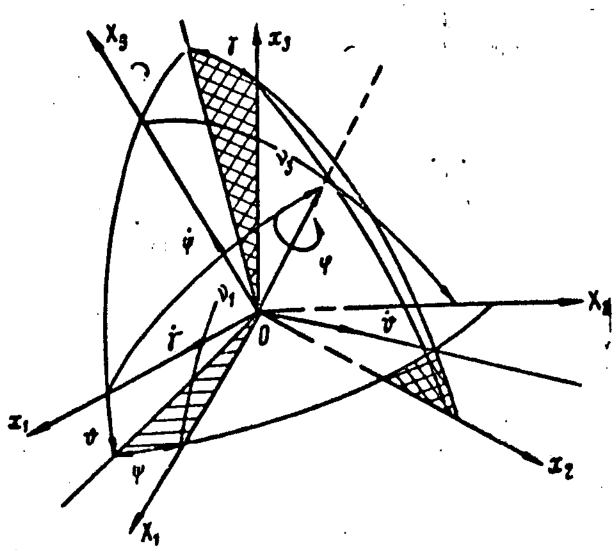


Figure 1 - 2

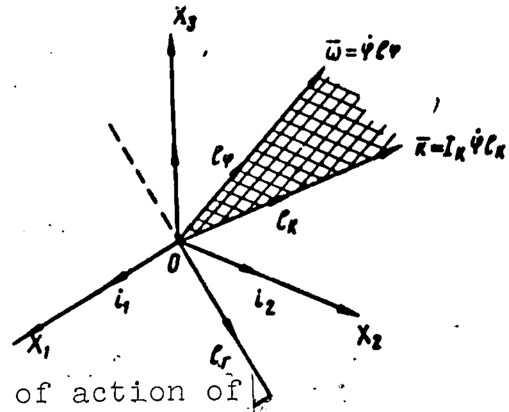
Let us follow the sequence of operations performed by the onboard computer. The geometry of the problem is shown in Figure 2. We shall give the computational operations used to determine the resulting angle of rotation ϕ, the direction of the Euler axis $l_\varphi = [\nu_1, \nu_2, \nu_3]$ (in the system $0x_1, x_2, x_3$ and $0X_1, X_2, X_3$), and the /13

sine of the angle of rotation, ϕ. From the measured initial values of ψ, ϑ and γ we determine the matrix of direction cosines $\alpha = \|\alpha_{ij}\|$; $i, j = 1, 2, 3$, in terms of which we calculate

$$\begin{aligned} \varphi &= \arccos \frac{1}{2}(\alpha_{11} + \alpha_{22} + \alpha_{33} - 1) \\ \nu_i &= \frac{\alpha_{i+2,i+1} - \alpha_{i+1,i+2}}{2 \sin \varphi} \\ \operatorname{sgn} \varphi &= \operatorname{sgn} \begin{Vmatrix} a_1 & b_1 & \nu_1 \\ a_2 & b_2 & \nu_2 \\ a_3 & b_3 & \nu_3 \end{Vmatrix} \quad \begin{matrix} a \neq l \\ b = \alpha a \end{matrix} \end{aligned} \qquad (2)$$

The execution of the last operation sine ϕ is most time-consuming.

A knowledge of the direction of the Euler axis determines the direction of the kinetic moment vector and of the axis of action of the gyroscopic moment (Figure 3).



Axes of action of gyroscopic moment

Figure 3.

The directions of these vectors are found from the formulas

$$l_k = \sum_{s=1}^{3} \frac{I_s \nu_s}{I_k} i_s$$

If

$$I_\varepsilon = \begin{Vmatrix} I_1 & 0 & 0 \\ 0 & I_2 & 0 \\ 0 & 0 & I_3 \end{Vmatrix} \qquad (4)$$

then

$$I_k = \sqrt{\sum_{s=1}^{3} I_s^2 \nu_s^2} \qquad (5)$$

where /14

$$I_r = \sqrt{\sum_{s=1}^{3} (I_{s+2} - I_{s+1})^2 \nu_{s+1}^2 \nu_{s+2}^2}$$

Here i_s — are the unit vectors of the attached coordinate system. We know that the unit vector in the direction of the Euler axis is $l_\varphi = \sum_{s=1}^{3} \nu_s i_s$.

A knowledge of the orientation of l_ϕ, l_k, and l_r enables us to give the direction $l_m = \sum_s^1 \beta_m i_s$ of the axis of action of the resultant momentum vector $\overline{M}$ and to write in an implicit form (in terms of the angle θ) the expressions for its direction cosines (Figure 4)

$$\left.\begin{aligned} \beta_n &= (\tilde{a}_n + b_n \operatorname{tg}\Theta)\cos\Theta \\ a_n &= \frac{I_n \nu_n}{I_k}; \quad |\tilde{a}_n| = a_n \\ \tilde{b}_n &= \frac{(I_{n+2} - I_{n+1})}{I_s} \nu_{i+1} \nu_{i+2} \quad |\tilde{b}_n| = b_n \\ \beta_s^* &= |\beta_n|_{max} \end{aligned}\right\} \quad (6)$$

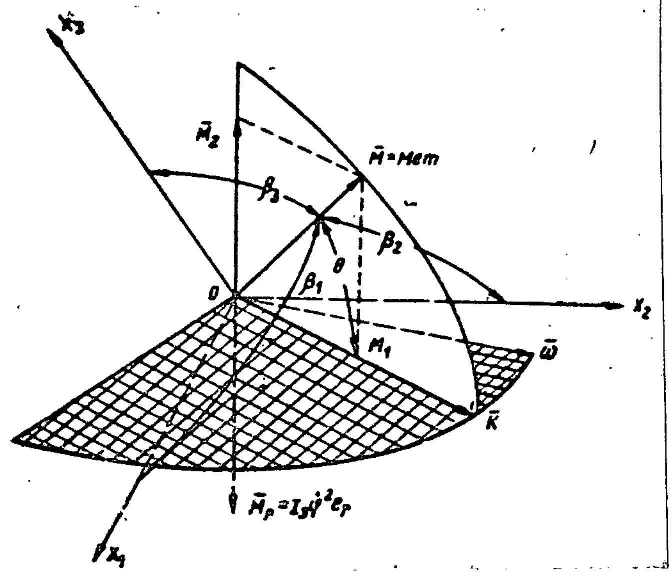


Figure 4

Denoting the maximum permissible value of the moment applied to the aircraft along the attached axes as M_{ms} and the maximum value of the direction cosine as β_s^*, we find that the maximum value of the modulus of (the vector) M is

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$$|\overline{M}|_{max} = \frac{M_{ms}}{\beta_s^*} \quad (7)$$

Then the equations of motion of the aircraft can be written on the basis of the conditions of the compensation of the dynamic reactions of the aircraft to the applied control moment in the following way:

The equations of motion are

$$\ddot{\varphi} = \frac{M}{I_k}\cos\Theta = \frac{M_{ms}}{I_k\,|a_s \pm b_s \operatorname{tg}\Theta|} \tag{8}$$

$$\dot{\varphi}^2 = \frac{M}{I_s}\sin\Theta = \frac{M_{ms}}{I_s}\,\frac{\operatorname{tg}\Theta}{|a_s \pm b_s \operatorname{tg}\Theta|} \tag{9}$$

The subsequent computational procedure for the synthesis of the system is presented without explanations.

Synthesis of the System

$$\text{a) } I = \int_0^T dt = \min \tag{10}$$

$$t_1 = \frac{1}{n}\operatorname{arc\,th}\sqrt{\operatorname{th}\frac{I_k a_s n^2 \varphi}{M_{ms}}} \text{ for 1)} \tag{11}$$

or

$$t_1 = \frac{1}{n}\operatorname{arc\,th}\sqrt{\operatorname{th}\frac{I_k a_s n^2 \varphi}{M_{ms}}} \tag{12}$$

$$T_m = \frac{1}{n}\left[\operatorname{arc\,th}\sqrt{\operatorname{th}\frac{I_k a_s n^2 \varphi}{M_{ms}}} + \operatorname{arc\,th}\sqrt{\operatorname{th}\frac{I_k a_s n^2 \varphi}{M_{ms}}}\right] \text{ for 2)} \tag{13}$$

For $0 \leqslant t \leqslant t_1$ and 1)

$$M_s = M_{ms}\frac{\beta_s}{\beta_s^*} \tag{14}$$

$$M_{s+i} = M_{ms}\frac{\tilde{a}_{s+i} + \tilde{b}_{s+i}\frac{a_s}{b_s}\cdot \operatorname{sh} nt}{a_s \operatorname{ch}^2 nt} \tag{15}$$

and 2)

$$M_s = M_{ms} = \frac{\beta_s}{\beta_s^*} \tag{16}$$

$$M_{s+i} = M_{ms}\frac{\tilde{a}_{s+i} + \tilde{b}_{s+i}\frac{a_s}{b_s}\sin^2 nt}{a_s \cos^2 nt} \tag{17}$$

For $t_1 < t < T$ and 2)

$$M_s = M_{ms}\frac{\beta_s}{\beta_s^*} \tag{18}$$

$$M_{s+i} = M_{ms}\frac{\left[a_{s+i}+b_{s+i}\frac{a_s}{b_s}\sin^2[x(t-t_1)]\right]}{a_s\cos^2[x-n(t-t_1)]} \tag{19}$$

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$$\text{и } 2)\ M_s = M_{ms}\frac{\beta_s}{\beta_s^*} \tag{20}$$

$$M_{s+i} = M_{ms}\frac{\left[a_{s+i}+b_{s+i}\,\mathrm{sh}^2[x-n(t-t_1)]\right]}{a_s\,\mathrm{ch}^2[x-n(t-t_1)]} \tag{21}$$

$$i = 1,2 \quad x = \operatorname{arc\,tg\,th} nt_1 \tag{22}$$

$$\text{б) } I = \int_0^T \sum_{n=1}^{3} K_n |M_n|\, dt = \min \tag{23}$$

$$t_1 = \frac{T}{4}\left[1-\sqrt{1-\frac{8I_b a_s \varphi}{T^2 M_{ms}}}\right] \tag{24}$$

$$t_2 = \frac{T}{2}\left[1+\sqrt{1-\frac{8I_b a_s \varphi}{T^2 M_{ms}}}\right] \tag{25}$$

for $t_1 < t < t_1 + t_2$

$$M = \frac{M_{ms}}{b_s}\,\mathrm{th}^2\, nt_1 \tag{26}$$

$$M_i = \frac{M_{ms}}{b_s}\,\mathrm{th}^2\, nt_1 \cdot b_i \quad i = 1,2,3 \tag{27}$$

The existence of the analytic solution of the problem involving the control of the three-dimensional turn maneuver enables us to use the on-board digital computer as the command computing unit (Figure 5). Such an application of the onboard computer excludes the

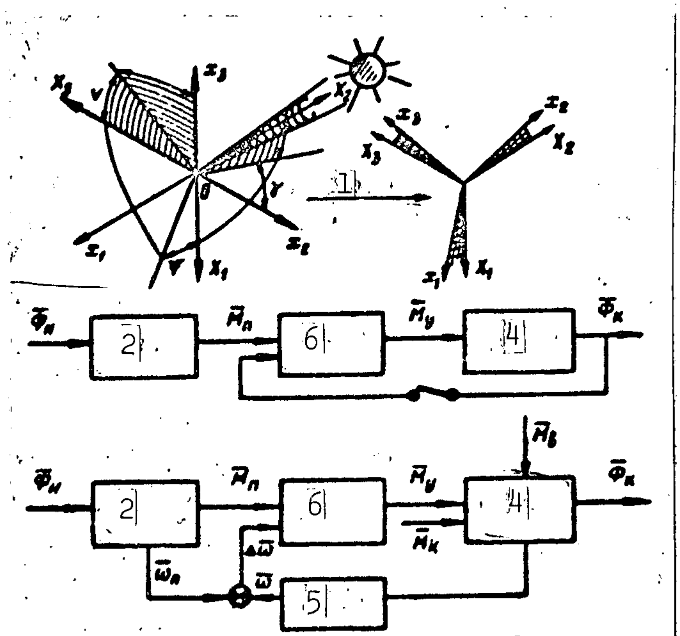


Figure 5.

1 — control problem; 2 — digital computer; 3 — control part of system; 4 — object; 5 — automatic control device; 6 — expansion unknown.

introduction of any feedback loops (rigid program). However, this does not imply the existence of such loops in the control part of the system and in the elimination of small angular deviations. /18

When making a turn by $\phi = 180°$ the effect of the external disturbances may result in an inadmissibly large error in the final angular position of the aircraft. For this reason corrections become necessary. The latter may be realized by maintaining the programmed angular velocity of the aircraft (Figure 6). Then the functions of the onboard digital computer become somewhat wider, but its purpose remains as before.

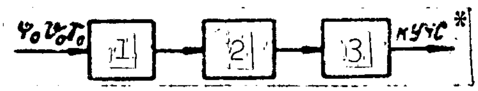


Figure 6. Structure of the command onboard digital computer

1 — unit for computing the kinematic parameters of motion; 2 — unit for computing the dynamic parameters of motion; 3 — unit for computing the programmed values of the control moments.

*expansion unknown

In its structure an onboard digital computer, containing the arithmetical and logical units, may be subdivided into three blocks whose functions are to compute:

1) kinematic parameters,
2) dynamic parameters,
3) programmed values of the controlled moments.

A general characterization of one of such blocks is given in Figure 7. It can be seen that the realization of extensive control with the aid of simple computing units is impossible. The functions performed by the other block are described in Figures 8 and 9.

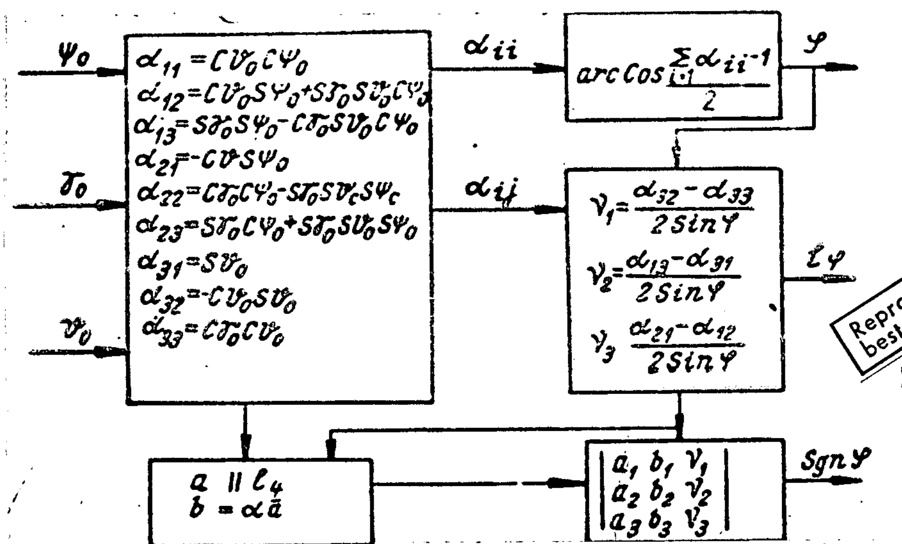
Functions of the unit for computing
the kinematic parameters of motion

∿ 300 operations of addition

∿ 200 operations of multiplication

∿ 40 operations of division

∿ 250 transfer to the storage unit (with commands)



	+	×	÷	No. of transfers to storage unit
$\sin\psi_0(\vartheta_0\gamma_0)$	84	54	12	120
$\cos\psi_0(\vartheta_0\gamma_0)$	87	54	12	120
α_{ij}	4	16	—	—
$\arccos\frac{\sum_{i=1}\alpha_{ii}-1}{2}$	33	28	5	43
l_φ	31	21	7	47
$\mathrm{Sgn}\,\varphi$	12	21	—	—

Figure 7

An important problem arises in the control of orientation /19 with adaptation. Such a control occurs when the moments of inertia of the aircraft either undergo significant changes or are to be determined during flight. An investigation of the problem shows that it is useful also in this case to retain the functions of the onboard digital computer designed to secure optimal control, as described above. However, there appears a new function of the onboard computer, related to the solution

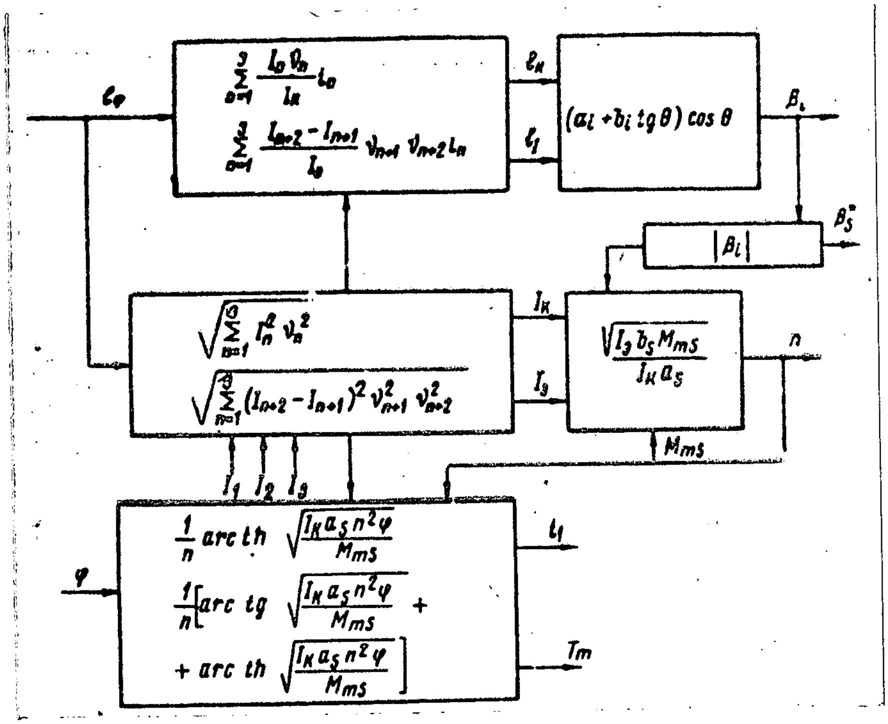


Figure 8

Functions of the unit computing dynamic
motion paramtters

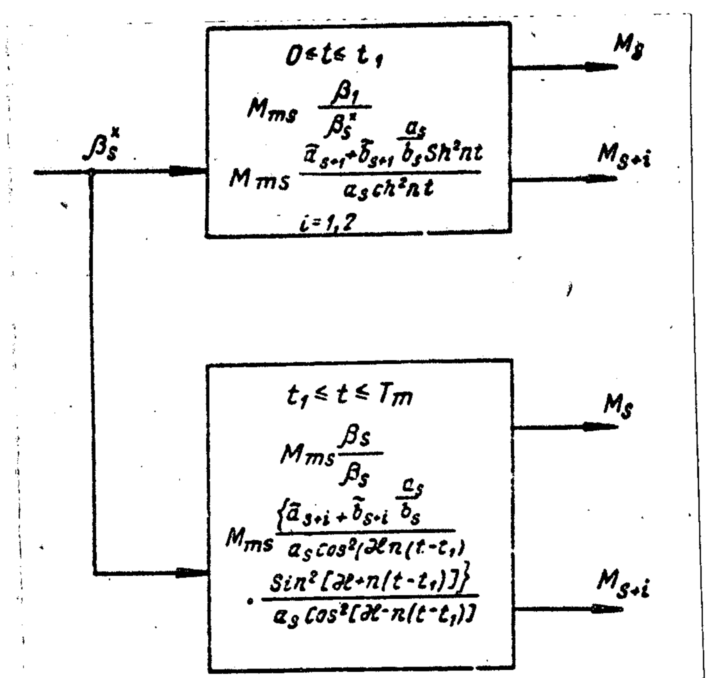


Figure 9

Functions of the block for computing the
programmed values of the controlled moments

of object recognition. It is characteristic that this function is performed by the onboard computer within a closed control loop.

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